Phytoplankton in the Beaufort and Chukchi Seas: Distributions, dynamics and environmental forcing

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Abstract: Time-series of remotely sensed distributions of phytoplankton, sea ice, surface temperature, albedo, and clouds were examined to evaluate the impact of the variability of environmental conditions and physical forcing on the phytoplankton distribution in the Beaufort and Chukchi Seas. Large-scale distributions of these parameters were studied for the first time using weekly and monthly composites from April 1998 through September 2002. The basic data set used in this study are phytoplankton pigment concentration derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), ice concentration obtained from the Special Sensor Microwave Imager (SSM/I) and surface temperature, cloud cover, and albedo derived from the Advanced Very High Resolution Radiometer (AVHRR). Seasonal variations of the sea ice cover was observed to be the dominant environmental factor as the ice edge blooms followed the retreating marginal ice zones northward. Blooms were most prominent in the southwestern Chukchi Sea, and were especially persistent immediately north of the Bering Strait in nutrient-rich Anadyr water and in some fronts. Chlorophyll concentrations are shown to increase from a nominal value during onset of melt in April to a maximum value in mid-spring or summer depending on location. Large interannual variability of ice cover and phytoplankton distributions was observed with the year 1998 being uniquely associated with an early season occurrence of a massive bloom. This is postulated to be caused in part by a rapid response of phytoplankton to an early retreat of the sea ice cover in the Beaufort Sea region. Correlation analyses showed relatively high negative correlation between chlorophyll and ice concentration with the correlation being highest in May, the correlation coefficient being -0.45. 1998 was also the warmest among the five years globally and the sea ice cover was least extensive in the Beaufort/Chukchi Sea region, partly because of the 1997-98 El Niño. Strong correlations were noted between ice extent and surface temperature, the correlation coefficient being highest at -0.79 in April, during the onset of the bloom period

Popular Summary: There have been several studies indicating amplified warming and a rapidly declining perennial ice cover in the Arctic. At present, very little is known about the impact of these phenomena on the biology of in the Arctic Ocean although considerable impacts over land have already been observed. This study make use of time-series satellite observations of phytoplankton, sea ice, surface temperature, albedo, and clouds in combination with in-situ measurements to gain insights into the effect of the variability of environmental conditions and physical forcing on phytoplankton distributions in the Arctic and more specifically in the Beaufort and Chukchi Seas. Large-scale distributions of these parameters were studied for the first time using weekly and monthly composites from April 1998 through September 2002. Seasonal variations of the sea ice cover dominated environmental conditions, and ice edge blooms followed retreating marginal ice zones northward. Blooms were most prominent in the southwestern Chukchi Sea, and were especially persistent immediately north of the Bering Strait in nutrient-rich Anadyr water and in some fronts. Chlorophyll concentrations increased from April to reach a maximum value in spring or summer depending on location. Large interannual variability of ice cover and phytoplankton distributions were observed. It is fortuitous that one of years in the study period is 1998 which is the warmest year globally during the last century. In 1998, sea ice retreated early in the Beaufort Sea resulting in a rapid response by phytoplankton and an early season massive bloom which was not observed during the other years. Correlation analyses showed relatively high negative correlation, as expected, between chlorophyll and ice cover area. Relatively strong correlations were also noted between ice extent and surface temperature, cloud cover, and albedo.

Significant Findings: Time-series of remotely sensed distributions of phytoplankton, sea ice, surface temperature, albedo, and clouds were examined to evaluate the impact of the variability of environmental conditions and physical forcing on the phytoplankton distributions in the Beaufort and Chukchi Seas. Seasonal variations of ice cover was observed to be the dominant environmental factor as the ice edge blooms followed the retreating marginal ice zones northward. Blooms were most prominent in the southwestern Chukchi Sea, and were especially persistent immediately north of the Bering Strait in nutrient-rich Anadyr water and in some fronts. Chlorophyll concentrations are shown to increase from a nominal value during onset of melt in April to a maximum value in mid-spring or summer depending on location. Large interannual variability of ice cover and phytoplankton distributions was observed with the year 1998 being uniquely associated with an early season occurrence of a massive bloom. This is postulated to be caused in part by a rapid response of phytoplankton to an early retreat of the sea ice cover in the Beaufort Sea region. Correlation analyses showed relatively high negative correlation between chlorophyll and ice concentration with the correlation being highest in May, the correlation coefficient being -0.45. 1998 was also the warmest among the five years globally and the sea ice cover was least extensive in the Beaufort/Chukchi Sea region, partly because of the 1997-98 El Niño. Strong correlations were noted between ice extent and surface temperature, the correlation coefficient being highest at -0.79 in April, during the onset of the bloom period.

Abstract

Time-series of remotely sensed distributions of phytoplankton, sea ice, surface temperature, albedo, and clouds were examined to evaluate the impact of the variability of environmental conditions and physical forcing on the phytoplankton pigment concentrations in the Beaufort and Chukchi Seas. Large-scale distributions of these parameters were studied for the first time using weekly and monthly composites from April 1998 through September 2002. The basic data set used in this study are phytoplankton pigment concentration derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), ice concentration obtained from the Special Sensor Microwave Imager (SSM/I) and surface temperature, cloud cover, and albedo derived from the Advanced Very High Resolution Radiometer (AVHRR). Seasonal variations of ice cover was observed to be the dominant environmental factor as the ice edge blooms followed the retreating marginal ice zones northward. Blooms were most prominent in the southwestern Chukchi Sea, and were especially persistent immediately north of the Bering Strait in nutrient-rich Anadyr water and in some fronts. Chlorophyll concentrations are shown to increase from a nominal value during the onset of melt in April to a maximum value in mid-spring or summer depending on location. Large interannual variability of ice cover and phytoplankton distributions was observed with the year 1998 being uniquely associated with an early season occurrence of a massive bloom. This is postulated to be caused in part by a rapid response of phytoplankton to an early retreat of the sea ice cover in the Beaufort Sea region. Correlation analyses showed relatively high negative correlation between chlorophyll and ice concentration with the correlation being highest in May, the correlation coefficient being -0.45. 1998 was also

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1. Introduction

Studies of the spatial and temporal variability of phytoplankton in the ocean are important to evaluate the location and magnitude of marine primary productivity that is approximately half of that of global productivity. Satellite remote sensing technology allows for accurate global retrievals of chlorophyll *a* concentration (Chl), a proxy for phytoplankton biomass, from space. Ocean color data from the Coastal Zone Color Scanner (CZCS) provided an unprecedented view of a large variety of biological processes in various regions of the world ocean (Gregg and Conkright, 2001; Yoder et al., 1993). However, data from the CZCS sensor are limited in spatial and temporal coverage. Since its launch in 1997, the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) has provided synoptic and continuous ocean color observations, which allow studies of both seasonal and interannual variability of phytoplankton.

Large, shallow (< 100 m water depth) continental shelves occupy approximately 30% of the total surface area of the Arctic Ocean. These shelf seas are seasonally ice free and are the sites of strong air-sea-ice exchanges, biological production, riverine discharges, and water mass transformation (Aagaard et al., 1981; Aagaard et al., 1985; Jones and Anderson, 1986; Macdonald and Wong, 1987). Among shelves, the Chukchi Sea is unique in that the northward transport of Pacific waters through Bering Strait profoundly influences the regional circulation, water mass properties, and nutrient distributions (Walsh et al., 1989; Weingartner et al., 1998). The Beaufort shelf is also important because it is relatively narrow but has one of the lowest salinity among Arctic shelf waters since it receives a large influx of fresh water from the Mackenzie River. This discharge occurs mostly in spring with reduced flow during summer.

It has been suggested that climate changes can be amplified in the Arctic because of positive feedback effects associated with the high albedo of ice and snow (Manabe et al., 1992). Some recent studies reported that the sea ice cover in the Northern Hemisphere has been decreasing in extent at a rate of about 3% per decade (Bjorgo et al., 1997; Parkinson et al., 1999). What is more remarkable is that the Arctic perennial sea ice cover, or ice that survives the summer, has been retreating at a rapid rate of 9% per decade (Comiso, 2002). Despite its importance, the Arctic remains poorly known because of general inaccessibility and adverse weather conditions in the region. Recent studies (Onstott and Shuchman, 1990; Comiso, 1991) have shown that satellite remote sensing is the most practical and effective way to investigate time-series of various key physical and biological processes in the high latitude regions. Comiso et al. (1993) investigated spatial and seasonal variability of phytoplankton distributions in the Southern Ocean using the CZCS data versus a variety of environmental variables. A similar study in the Barents Sea by Mitchell et al. (1991) also used the CZCS data with more limited spatial and temporal coverage. Physical forcing of phytoplankton dynamics at large time- and space-scales is best studied with satellites which allow for detailed characterization of changes in phytoplankton biomass and productivity in response to inter-annual events like El

Niño-La Niña (Kahru and Mitchell, 2000; 2001) and the Arctic Oscillation (Thompson and Wallace, 1998).

Seasonal changes in ice cover define many polar marine ecosystems. The breakup of sea ice in spring-summer is very important for phytoplankton in that it provides a stable surface layer with abundant supply of light that is needed in photosynthesis (Sakshaug, 1989). This study aims to improve our understanding of temporal and spatial variability of phytoplankton distribution in this region. An important objective is to explore the relationship between phytoplankton blooms and sea ice retreat that can now be conveniently documented via remote sensing. In this paper, large scale spatial distributions of phytoplankton in the Beaufort and Chukchi Seas are studied using imagery from SeaWiFS in conjunction with data from other satellites. Seasonal and interannual variability of phytoplankton are explored with five years of ocean color data from 1998 to 2002. In the ocean, biological activities are intimately linked to physical processes. Correlation analyses between chlorophyll concentration and various geophysical parameters including ice concentration and surface temperature are conducted with a view of evaluating the impact of physical forcing on biological processes.

2. Materials and Methods

2.1. Study area

Figure 1 shows the western Arctic including the Beaufort and Chukchi Seas. The study area is bordered by Wrangle Island (180°W) to the west, Banks Island (120°W) to the east, Bering Strait to the south (66°N), and 75°N latitude in the north to include all major areas of open water. In this study, the whole region was separated into the Beaufort Sea and the Chukchi Sea at Point Barrow using 156.5°W longitude. The wide shelf of the Chukchi Sea extends up to 300 km but is relatively shallow with depths of 30-50 m. Two bathymetric features, namely Herald Canyon and Barrow Canyon, are important for topographic steering of cross-shelf transport. The Beaufort Sea shelf is relatively narrow, extending only about 50-100 km off the coast and typically < 100 m deep.

2.2. Ocean color data

Remotely sensed chlorophyll concentrations observed by SeaWiFS aboard SeaStar (operated by Orbimage Corporation) are the main source of ocean color data for the present work. SeaWiFS data provide good spatial and temporal coverage and have been widely used in ocean color studies. However, chlorophyll concentrations retrieved from the global SeaWiFS algorithm may not be the most appropriate for regional analysis, especially for the high latitude regions where bio-optical properties are distinctively different (Mitchell and Holm-Hansen, 1991; Mitchell, 1992; Cota et al., 2003; Cota et al., 2004). In this study, daily SeaWiFS data (after the 4^{th} reprocessing) were transformed by linear interpolations to generate chlorophyll *a* concentrations for the Arctic. The linear interpolation scheme was developed by Cota et al. (2004). The transformation produces more accurate chlorophyll values for the Beaufort and Chukchi Seas but preserves the spatial and temporal patterns in the original SeaWiFS images (Comiso and Cota, in review). Weekly and monthly averages of SeaWiFS ocean color data from April to September for five years (1998-2002) were obtained from the transformed daily data.

2.3. Geophysical parameters

Environmental factors regulate the spatial and temporal variability of phytoplankton distributions. Relationships between ocean color and key geophysical parameters were studied to better understand interactions between physical processes and biological activities. Among them, sea ice cover is of particular interest because the retreat of sea ice in spring promotes phytoplankton blooms (Sakshaug, 1989). This process was studied with satellites using CZCS chl-a and SSM/I sea ice data for the Barents Sea (Mitchell et al., 1991). The passive microwave data from the Special Sensor Microwave Imager (SSM/I) provided the weekly mean sea ice concentrations (Comiso et al., 1997). Surface temperature data (different from SST) were acquired from thermal infrared data from the Advanced Very High Resolution Radiometer (AVHRR). Cloud statistics and albedo were also derived from the AVHRR sensor (Comiso, 2001). Wind data from the European Centre for Medium-Range Weather Forecasting (ECMWF) were used to study the effects of wind speed on phytoplankton distributions.

2.4. Data fusion

Geophysical data from different sensors and SeaWiFS ocean color data were processed and remapped onto the polar stereographic grid with a resolution of 12.5 by 12.5 km, which is sufficient for studies of regional variability. The uniform grid allows pixel-by-pixel comparisons for all parameters. There were frequently no data for ocean color observations because of ice and cloud cover. Time averaging was done using all data available within the week at each pixel to produce weekly means. The spatially and temporally averaged data were used in correlation analyses for ocean color with various geophysical parameters.

3. Results and discussion

3.1. Spatial variability

During late summer, the extensive sea ice in the Arctic Ocean reaches its minimum. Phytoplankton in the Arctic can be observed by satellite ocean color in open water only after most sea ice melts. Figure 2 shows the monthly phytoplankton distributions derived from SeaWiFS for the Beaufort and Chukchi Seas for the growing season from April to September 1998.

As ice retreats in this region, the seasonal progression of phytoplankton biomass becomes evident. The spatial variability of phytoplankton over the growth season is apparent in Figure 2. The sea ice retreat is not uniform and results in indentations in the ice pack, especially in July (Fig. 2). Blooms along ice edge are common due to wind-driven upwelling. Because there is usually a 2-3 weeks lag between chlorophyll maximum and ice retreat, some relatively low chlorophyll concentrations are observed along the ice edge.

High chlorophyll concentrations are observed in the southwestern Chukchi Sea and along the coast of the Beaufort Sea. It is well known that the Anadyr Current brings nutrient-rich water through the Bering Strait. The northward flow is sustained by the sea level difference between the Bering Sea and the Arctic Ocean. The flow field divides into at least two regimes north of Bering Strait. The low-salinity, nutrient-poor fraction on the east continues along the northeastern coast as the Alaska Coastal Current (ACC), and to the west the high-salinity, nutrient-rich portion flows to the north and through Hope Valley and Herald Canyon (Coachman et al., 1975; Walsh et al., 1989). Primary production rates in the southwestern Chukchi Sea are among the highest ever recorded, but much lower values are found in the Alaskan coastal waters (Walsh et al., 1989; Springer and McRoy, 1993). On the outer Chukchi shelf, there is modest production decreasing into the basin (Cota et al., 1996)

The Beaufort shelf is relatively narrow and ice covered most of the year, which results in relatively low production. However, new production based on nitrate drawdown has been estimated to 20 g C m^{-2} yr^{-1} in the Mackenzie Shelf (Macdonald and Wong, 1987). The interaction between river plume and seawater occurs on the open shelf due to the strong discharge of the Mackenzie River. Wind forcing and local circulation spread the river plume when little ice is present, as shown by high chlorophyll concentrations around the Mackenzie River mouth in Figure 2.

Two meridional transects along 150°W and 170°W (Figure 1) were chosen to illustrate the variations of phytoplankton biomass in the Beaufort and Chukchi Seas. The 150°W transect covers the shelf of Beaufort Sea but is distant from the mouth of Mackenzie River to minimize the effects of freshwater runoff. The 170°W transect intersects the Bering Strait and widest part of the Chukchi shelf. Monthly mean chlorophyll concentrations along the two transects are plotted in Figure 3 and 4, respectively. For the 150°W transect, high chlorophyll values are observed in August and September close to the Beaufort Sea coast, which has numerous shallow bays and lagoons. The very shallow inner shelf is strongly wind-driven in summer, while the dominant feature of the outer shelf is the eastward Beaufort Undercurrent. Furthermore, there are frequent cross-shelf exchanges associated with the transport of materials between the inner and outer shelf. Flows directed seaward are more common than landward ones (Aagaard, 1984). The flow events serve as a dispersal mechanism and chlorophyll concentrations are lower northward of the coast (Figure 3). It should be noted that large amounts of colored dissolved organic matter (CDOM) are transported to the sea from land by river discharges. The relatively high chlorophyll concentrations observed by SeaWiFS close to the Mackenzie River mouth (Figure 2) are associated, at least in part, with the presence riverine CDOM and resuspended sediments in shallower waters. The effect of CDOM on chlorophyll retrievals has been documented (Carder et al., 1989) but quantitative estimates of the bias caused by the contamination are not available.

Blooms with chlorophyll concentration higher than 1 mg m^{-3} are found from June to September along the 170°W transect across the Chukchi Sea shelf (Figure 4). Compared to the western Beaufort Sea, ocean color data in the Chukchi Sea are available two months earlier when the edge ice starts to retreat. Chlorophyll biomass also shows a pattern of decreasing northward, which shows that blooms are generally restricted to retreating ice edges and the nutrient-rich open waters in the southwestern part of Chukchi Sea close to the Bering Strait.

The near-surface distributions of phytoplankton vary with surface forcing. The phytoplankton distributional patterns are controlled by competing biological and physical processes (Steele, 1978) such that phytoplankton growth enhances the existing patterns and turbulent diffusion breaks down the surface patchiness. Recent studies have shown that in dynamic areas such as coastal upwelling zones, the normal spatial patterns produced by growth, death, and sinking of phytoplankton cannot persist through the dispersion of mesoscale turbulent motion (Denman and Abbott, 1994). The large-scale patterns of bloom evolution in the western Arctic are revealed by monthly averages, as in

Figure 2. The mesoscale patterns are better resolved with weekly data (Denman and Abbott, 1988), but because of cloud it is sometimes difficult to obtain spatial coverages as complete as those in the monthly averages.

3.2. Seasonal variability

Monthly averages of pigment concentrations from SeaWiFS (Figure 2) provide the means to study the seasonal evolution of phytoplankton distributions. The distributions in the Beaufort and Chukchi Seas are strongly affected by pack ice seasonally. This region was largely ice-covered from April to May in 1998, with only small open water area in the eastern Beaufort shelf. In June, phytoplankton blooms were observed as the sea ice retreated northward. Increases in phytoplankton biomass closely followed the onset of breakup. The dominant species are normally centric diatoms, which is characteristic of phytoplankton blooms in this region (Booth and Horner, 1997; Horner and Schrader, 1982). As ice receded during spring and summer, phytoplankton blooms extended farther north in the Chukchi Sea. Biomass continues to increase until September (Figure 4).

The weekly means of chlorophyll, ice concentration, and surface temperature for the Beaufort Sea and the Chukchi Sea are shown in Figure 5 and 6, respectively. Mean chlorophyll concentration for both regions displays high variability. Nevertheless, a seasonal trend shows that chlorophyll concentration reaches a maximum value between May and June, but the timing of the vernal bloom tracks the decrease in the ice cover (Figure 5A and 5B; Figure 6A and 6B). While the seasonal variations differ yearly, the single chlorophyll maximum in late spring or early summer is typical in the Arctic regions (Longhurst, 1995). The seasonal cycles of chlorophyll are associated with environmental factors which influence phytoplankton growth. Among them, light and nutrients are the two main factors. Sverdrup's model (1953) links the stability of surface water layer to light to explain the variations of phytoplankton growth. The stable surface prevents phytoplankton from being transported to deeper layers, where there is insufficient light, but also reduces vertical mixing of nutrients. In the Arctic, it is common that algal cells remain in this surface layer and grow until nutrients become limited.

The retreat of sea ice is a defining seasonal event for phytoplankton development. Seasonal changes in solar radiation and oceanic heat transport can cause major changes in the extent of ice cover. The average extent of sea ice in the Arctic varies from 8×10^6 km^2 in late August or early September to 15×10^6 km^2 in late February or March (Walsh and Johnson, 1979). The perennial pack ice is mostly confined to the deep basins of the Arctic Ocean in summer. In the study areas in the Beaufort and Chukchi Seas, the mean ice concentration decreases from about 80% in April to less than 10% in September (Figure 5B and 6B) for all five years (1998-2002). The increase in irradiance and a stable surface layer caused by melting ice enhance phytoplankton growth behind the retreating ice edge (Sakshaug, 1989).

The weekly mean of surface temperature for the Beaufort and Chukchi Seas are plotted in Figure 5C and 6C, respectively. Surface temperature increases dramatically as the ice cover changes from almost 100% ice in spring to less than 10% ice in summer. Data from all five years consistently show July as the warmest month following the seasonal peak in solar radiation. There is about a two-month lag between maximal surface temperature and open water area, because ice continues to melt through September with surface temperature above the freezing point.

3.3. Interannual variability

Interannual environmental variability in the Beaufort and Chukchi Seas during the 1998 to 2002 period has been observed to be considerable. Such variability should be evaluated in the context of the rapidly declining Arctic perennial ice cover during the last two decades (Comiso, 2002). In 1998 phytoplankton biomass increased much earlier in the Beaufort Sea, when ice concentration declined early (Figure 5A and 5B). For the Chukchi Sea, phytoplankton blooms occurred earliest in 2002 (Figure 6A). The yearly fluctuations of chlorophyll concentration (Figure 5A) show that biomass can peak up to two months later in cold years with more extensive ice cover. Overall, surface temperature and ice cover indicate that 1998 was the warmest among the five years while 2001 was the coldest year.

The evolution of phytoplankton biomass from April to September 2001 in a cold year is illustrated in Figure 7. Compared to a warm year in 1998 (Figure 2), the seasonal differences are apparent. The Beaufort Sea remained largely ice-covered in 2001 until late July, while in 1998 large open water areas were observed in May. Comiso et al. (2003) found that the areal extent of open water region in the Beaufort Sea was unusually high in 1998. Their results showed that the retreat of sea ice during 1998 was coherent with warming in both the atmosphere and the ocean in the region and with changing wind patterns.

To illustrate the interannual variability more quantitatively, the chlorophyll concentration, open water area, surface temperature, cloud statistics, and albedo for 1998 and 2001 for the Beaufort Sea and the Chukchi Sea are compared in Figure 8 and 9, respectively. This summary provides a quick assessment of interannual variability of multiple parameters. For the Beaufort Sea, mean chlorophyll concentration reached a maximum value in May 1998 (week 21), showing that phytoplankton peaked a month earlier in 1998 than in 2001 (Figure 8A & 8B). Most areas were ice covered until July in 2001. The open water area of the Beaufort Sea at the end of growth season was about 1.7×10^5 km^2 in 2001 versus 2.8×10^5 km^2 in 1998. The cumulative chlorophyll concentration (defined as the sum of the products of chlorophyll concentration and corresponding area for each pixel) in open water area in 1998 was twice of that in 2001. For each of the six months from April to September, surface temperature in 1998 was higher than in 2001, as shown in Figure 8E & 8F. Note that surface temperature in April and May 2001 was well below the freezing point, consistent with more extensive ice cover during that period. In Figure 8G & 8H, the cloud fraction increases from spring to summer, which confirms that higher cloud fraction usually corresponds to increased open water area. Compared to 2001, the surface albedo in spring of 1998 was lower (Figure 8I & 8J) and consistent with earlier onset of melt. Reduction of ice cover decreases the surface reflectivity and albedo. That the surface albedo reached minimum after June or July is consistent with more meltponding and minimal ice cover in summer. Comparing 1998 to 2001, the Chukchi Sea showed similar trends. Phytoplankton biomass also increased earlier in 1998 than in 2001 (Figure 9A and 9B). The open water area was about 3.0×10^5 km^2 for both years (Figure 9C and 9D). Temperature was higher in 1998 than in 2001 for the same time period (Figure 9E and 9F). Clouds showed a general seasonal increase corresponding to more open water area (Figure 9G and 9H), while albedo decreased from April to September (Figure 9I and 9J).

The interannual variability of ice concentration is further demonstrated in Figure 10 and 11 for the transects in 150°W and 170°W, respectively. In 1998, it was mostly ice free along the 150°W in the Beaufort Sea. By contrast, ice concentration was higher than 40% along this transect in August 2001. Only the southern part of the transect was ice free in September 2001 (Figure 10). The northward propagation of open water area is also clearly shown in Figure 11.

Changes in the Arctic climate have been studied in terms of changes in the Arctic Oscillation (AO) index which have been shown to follow an upward trend in recent years (Thompson and Wallace, 1998). The AO index is closely related to the variations of mean annual temperature in the Arctic (Overpeck et al., 1997). It has been suggested that the positive phases of the AO increases the ice cover and thickness in the Beaufort and Chukchi Seas by a combination of the anomalous mean surface heat flux and ice advection (Liu et al., 2004). The AO index has a positive trend of 0.15 per decade from 1978 to 2002 which would suggest an increasing ice cover in the western Arctic during this period which is opposite to what was observed. On the other hand, negative trend in the ENSO index is observed at -0.12/decade suggesting more ice in the Arctic (which was not observed) but less ice in the Chukchi and southern Beaufort Seas, which is consistent with actual satellite observations. During El Niño events, it was postulated that changes of regional Ferrel Cell cause anomalous poleward mean meridional heat flux into the sea ice zones in the northeast Pacific/northwest America region, which results in enhanced surface air temperature that limits the growth of sea ice in the Beaufort and

Chukchi Seas (Liu et al., 2004). The below normal ice conditions in the Bering Sea in March and April of 1998 and in the Beaufort and Chukchi Seas at a later date was thus likely in part, associated with El Niño of 1997-98.

3.4. Correlation analysis

The correlation analyses between chlorophyll concentration and ice cover and surface temperature were performed to examine the spatial relationships of these geophysical parameters to the phytoplankton biomass. While the simple linear correlation involving two variables at a time does not provide a complete description of the relationships of the three variables, the strength of each pair of variables can certainly be revealed. Since seasonal variations of chlorophyll are evident, the correlation analyses were performed for each month using data from all five years to study the seasonality and the correlation coefficients R are summarized in Table 1.

Correlations between chlorophyll and ice concentration are strongest in spring with R values of -0.18 and -0.451 in April and May, respectively (Table 1). The coherence of these two variables in spring is due to blooms tracking ice retreat in the Beaufort and Chukchi Seas. Breakup and ice melt trigger phytoplankton bloom as increasing light level, abundant nutrients, and low grazing pressure all favor phytoplankton growth. The retreating ice is the dominant factor in determining the spatial variability of phytoplankton distribution in spring. In later months, the correlation is relatively week with R values approaching zero in August and September (Table 1) when the whole region is almost ice free. Such low correlations are not unexpected because ice concentration is no longer the dominant forcing. Later in the year other factors including limited nutrients, wind, currents, and mixed layer depth may all have important effects on phytoplankton.

The correlation between chlorophyll concentration and surface temperature is generally positive for all six months (Table 1). Comiso et al. (1993) found negative correlation between chlorophyll and surface temperature in the Southern Ocean. They suggested conditions in winter were more favorable to blooming than in summer because phytoplankton in that region were better adapted to low temperatures, but iron depletion may play a larger role. For the Arctic and subarctic regions, Comiso et al. (in review) described a maximum temperature about 3-4°C beyond which phytoplankton biomass declined. This was attributed to nutrient drawdown, not a direct temperature effect on phytoplankton growth. Our results imply that the surface temperature is within the normal range for phytoplankton growth in the Beaufort and Chukchi Seas, and phytoplankton are acclimated to ambient temperature.

Our results showed weak correlation between chlorophyll and wind (Table 1). Wind-driven upwelling often contributes to phytoplankton bloom along ice edge. But in open water area wind also serves as a dispersal mechanism. Finer temporal and spatial scales are needed to look into the effects of wind.

Since ice concentration plays a very important role in determining the spatial and temporal variability of phytoplankton distribution, especially in spring, the correlation of ice concentration with surface temperature, cloud cover, and albedo were also analyzed to study the relationships between geophysical parameters. Correlation results are also summarized in Table 1. The correlation between ice cover and surface temperature is clearly negative as expected but the correlation coefficient is highest at -0.788 in April, during onset of phytoplankton blooms. Negative correlation also exists between ice concentration and cloud cover, with the only exception in April probably because the region is almost all ice covered at that time. Strong positive correlations are present between ice concentration and albedo because higher ice cover markedly increases the average surface reflectivity. The robust correlation between ice concentration and the three geophysical parameters helps explain temporal and spatial variability of phytoplankton distributions.

4. Summary and Conclusions

Five years of ocean color data from SeaWiFS were analyzed in conjunction with ancillary data, which includes sea ice concentration, surface temperature, cloud statistics, and albedo, to study and quantify the large scale spatial and temporal variability of phytoplankton distributions in the Beaufort and Chukchi Seas. Much of the northern part of this region is largely ice covered the year around. Only data in spring and summer growth season from April to September were used because of the presence of sea ice cover in the study area during other periods. Strong seasonality of the bloom patterns in this region was observed. Blooms were more pronounced in the southwestern part of the Chukchi Sea where Pacific waters continually import nutrients through the Bering Strait. There is a progression of ice edge blooms following seasonal ice retreat. Large interannual variability in the intensity of phytoplankton concentrations which was likely caused by the large interannual variability of the ice cover during the same period was observed. The latter was in part driven by atmospheric forcings, such as those associated with the Arctic Oscillation and El Niño-Southern Oscillation (ENSO) (Thompson and

Wallace, 1998; Moritz et al., 2002; Liu et al., 2004). The bloom patterns during the warmest and coldest years (namely, 1998, and 2001) during the 5-year period were studied and results show much higher pigment concentrations in 1998 than in 2001.

The phytoplankton distributions have been shown to be influenced by various environmental parameters and physical processes. The result of simple linear correlation shows a relatively strong inverse relationship between average phytoplankton biomass and average ice concentration in spring within each study area. Significant correlation between ice concentration and surface temperature, cloud cover, and albedo were also noted. The relationships between chlorophyll and some environmental factors are not expected to be linear but the simple correlation provides some insights into the sensitivity of the relationships and some information regarding the mechanistic links between the variables. There are other physical factors impacting the phytoplankton distribution including currents and bathymetry. Studies of their effects are beyond the scope of this paper.

This study provides detailed information about the large-scale temporal and spatial variability of phytoplankton distributions in the Beaufort and Chukchi Seas. However, the use of monthly averages and reduced resolution makes it difficult to resolve mesoscale patterns in the data (Denman and Abbott, 1988). Future work will involve in depth analysis of weekly high resolution data to study finer spatial and temporal patterns.

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Figure captions

Figure 1. Geographic map of the Western Arctic showing the location of Beaufort and Chukchi Seas. Land areas are shown in gray while ice and clouds are shown in white. The two study transects are along 150°W and 170°W which are shown in bold lines.

Figure 2. Monthly maps of chlorophyll concentration in April, May, June, July, August, and September 1998. Lands are shown in gray while ice and clouds are shown in white.

Figure 3. Chlorophyll concentration in August and September 1998 along the Beaufort Sea 150°W transect.

Figure 4. Chlorophyll concentration in June, July, August, and September 1998 along the Chukchi Sea 170°W transect.

Figure 5. Weekly averages of chlorophyll concentration (A), ice concentration (B), and surface temperature (C) for 1998, 1999, 2000, 2001, and 2002 for the Beaufort Sea.

Figure 6. Weekly averages of chlorophyll concentration (A), ice concentration (B), and surface temperature (C) for 1998, 1999, 2000, 2001, and 2002 for the Chukchi Sea.

Figure 7. Monthly maps of chlorophyll concentration in April, May, June, July, August, and September 2001. Lands are shown in gray while clouds and ice are shown in white.

Figure 8. Comparison of weekly averages of chlorophyll concentration (A &B), open water area(C & D), surface temperature (E & F), cloud cover (G & H), and albedo (I & J) in 1998 and 2001 for the Beaufort Sea.

Figure 9. Comparison of weekly averages of chlorophyll concentration (A &B), open water area(C & D), surface temperature (E & F), cloud cover (G & H), and albedo (I & J) in 1998 and 2001 for the Chukchi Sea.

Figure 10. Ice concentration in August and September 1998 (filled circle) and 2001 (unfilled circle) along the Beaufort Sea 150°W transect.

Figure 11. Ice concentration in June, July, August, and September 1998 (filled circle) and 2001 (unfilled circle) along the Chukchi Sea 170°W transect.

Table 1. Results of correlation analyses between two variables for each month from April to September (Chl is chlorophyll concentration and ST is surface temperature).

Correlation	April	May	June	July	August	September
R(Chl, Ice)	-0.180	-0.451	-0.039	0.130	-0.007	-0.097
R(Chl, ST)	0.290	0.211	0.383	0.245	0.186	0.281
R(Chl, Wind)	-0.163	-0.017	-0.044	-0.091	0.005	-0.173
R(Ice, Clouds)	0.314	-0.141	-0.589	-0.677	-0.786	-0.730
R(Ice, Albedo)	0.828	0.804	0.874	0.832	0.747	0.657
R(Ice, ST)	-0.788	-0.458	-0.140	-0.456	-0.557	-0.506

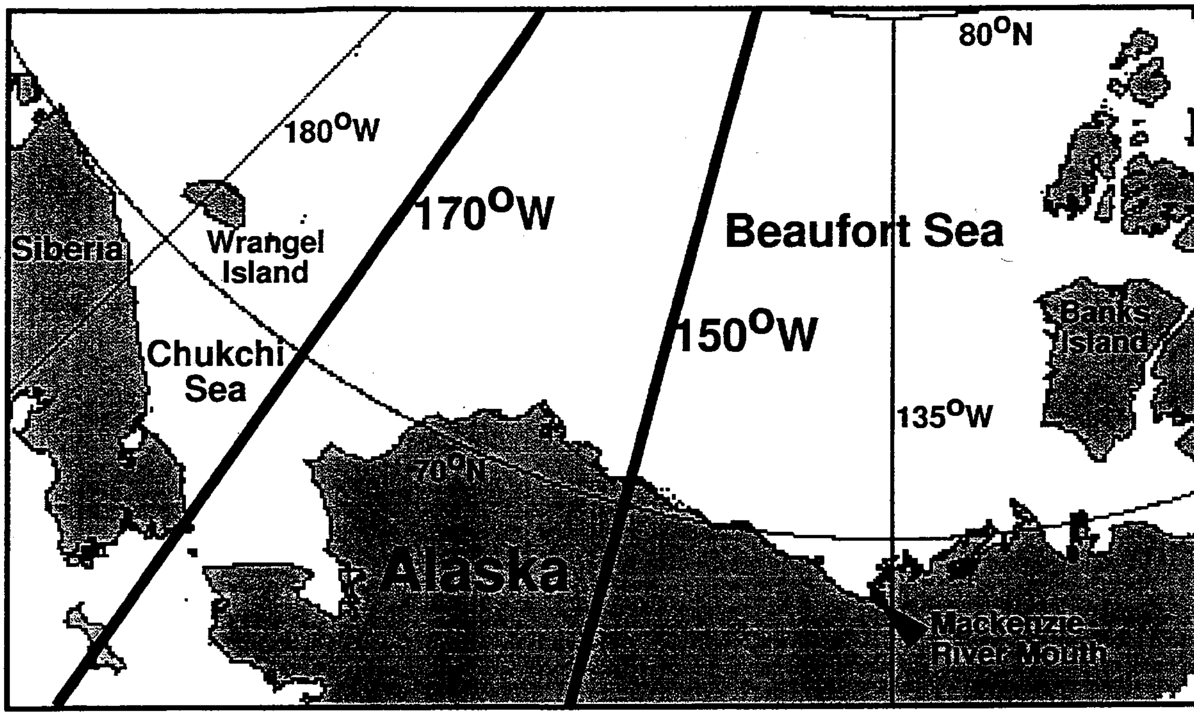
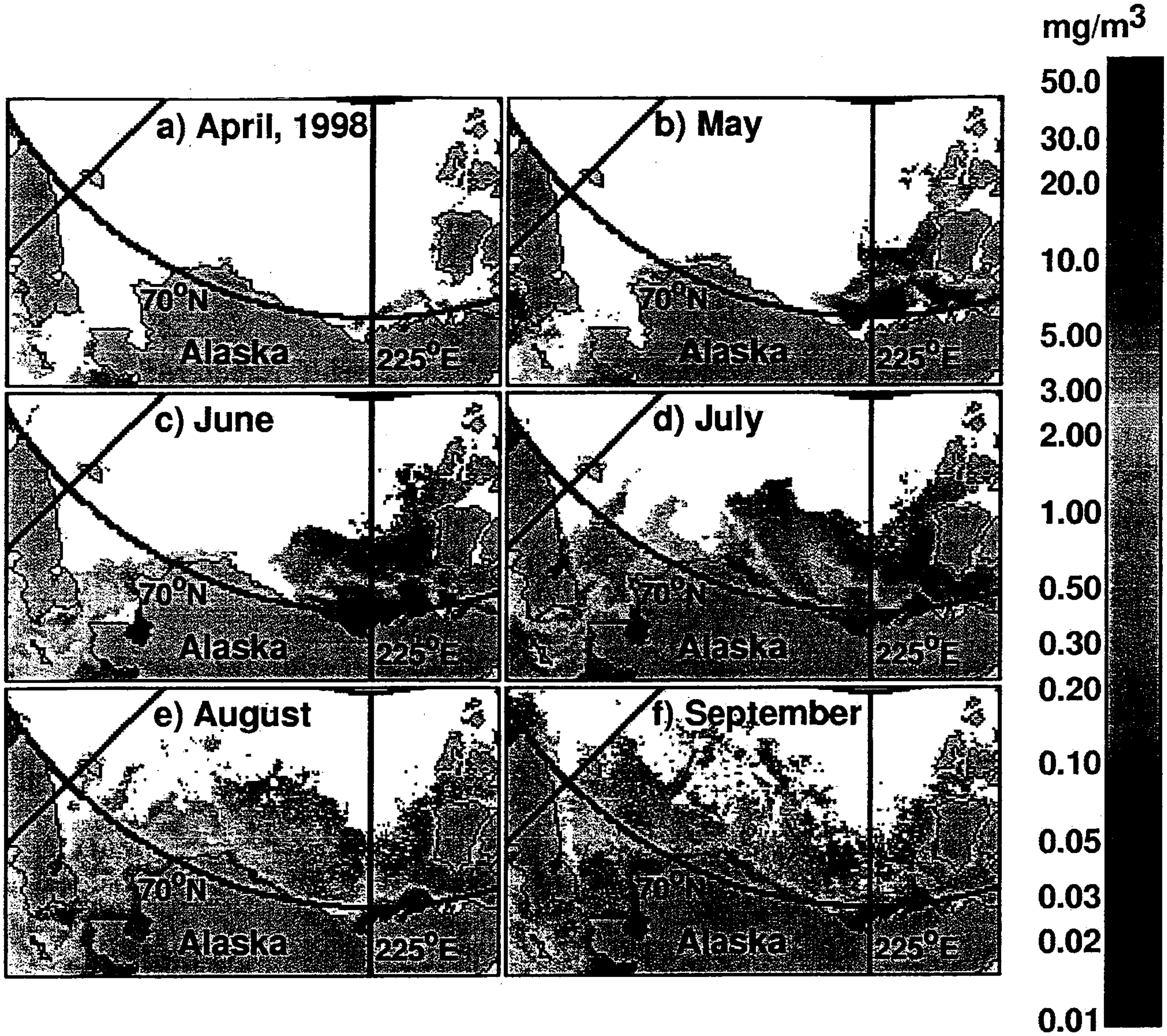

80°N
180°W
170°W
Beaufort Sea
Siberia
Wrangel
Island
Chukchi
Sea
150°W
Banks
Island
135°W
70°N
Alaska
Mackenzie
River Mouth

Fig. 1



mg/m3
50.0
30.0
20.0
10.0
5.00
3.00
2.00
1.00
0.50
0.30
0.20
0.10
0.05
0.03
0.02
0.01
a) April, 1998
b) May
c) June
d) July
e) August
f) September
70°N
Alaska
225°E

Fig. 2

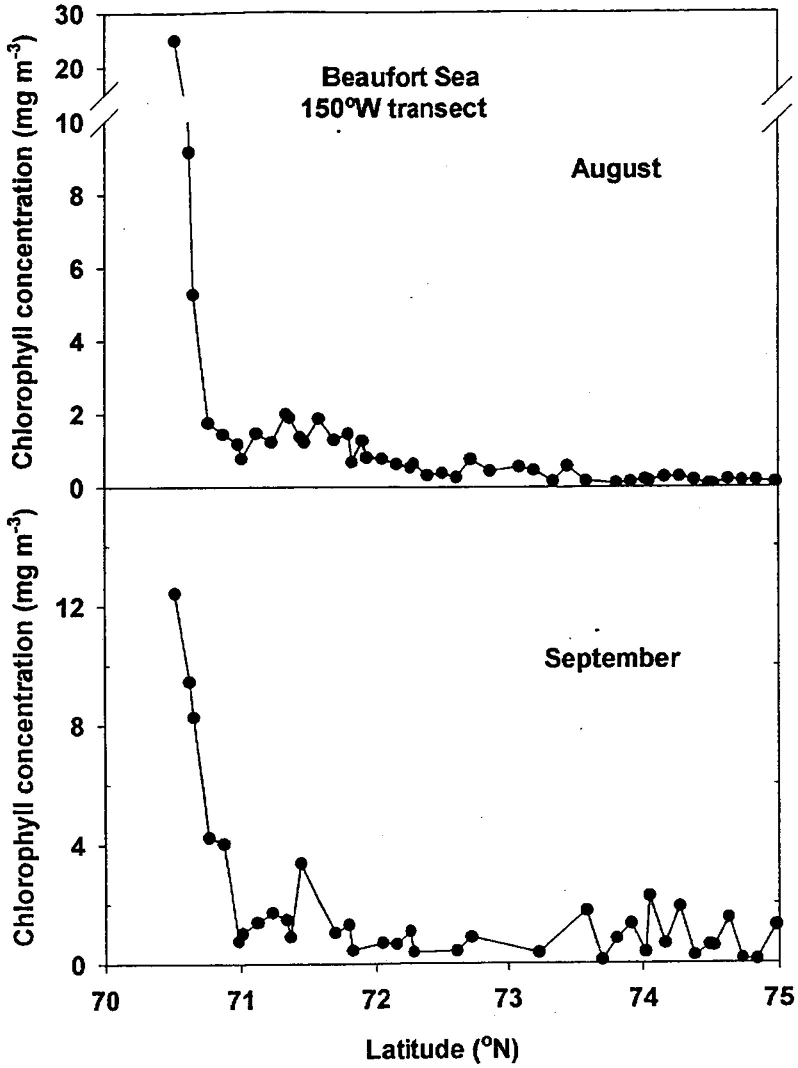

30
20
10
8
6
4
2
0
Chlorophyll concentration (mg m-3)
Beaufort Sea
150°W transect
August
12
8
4
0
Chlorophyll concentration (mg m-3)
September
70
71
72
73
74
75
Latitude (°N)

Fig. 3

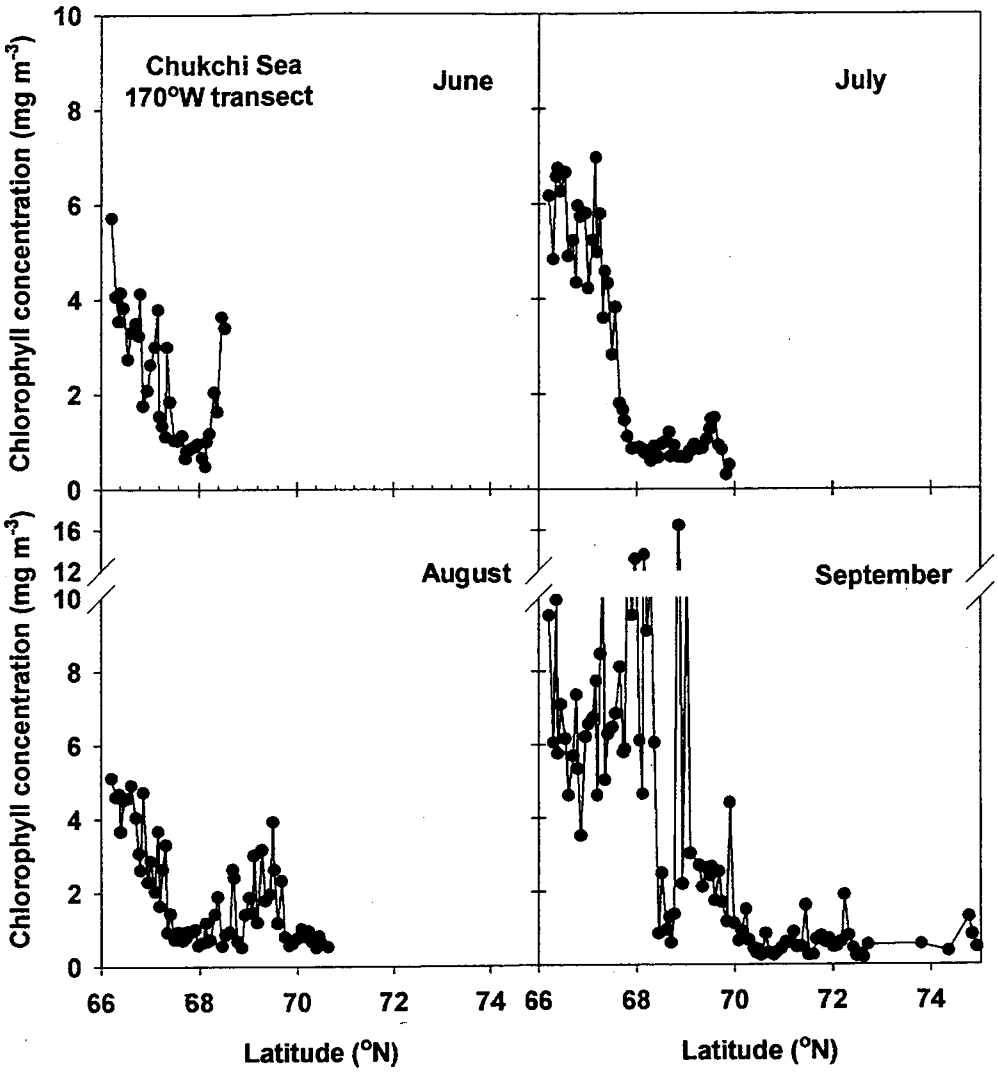

Chukchi Sea
170°W transect
June
July
August
September
Chlorophyll concentration (mg m-3)
Chlorophyll concentration (mg m-3)
Latitude (°N)
Latitude (°N)
0
2
4
6
8
10
12
16
66
68
70
72
74

Fig. 4

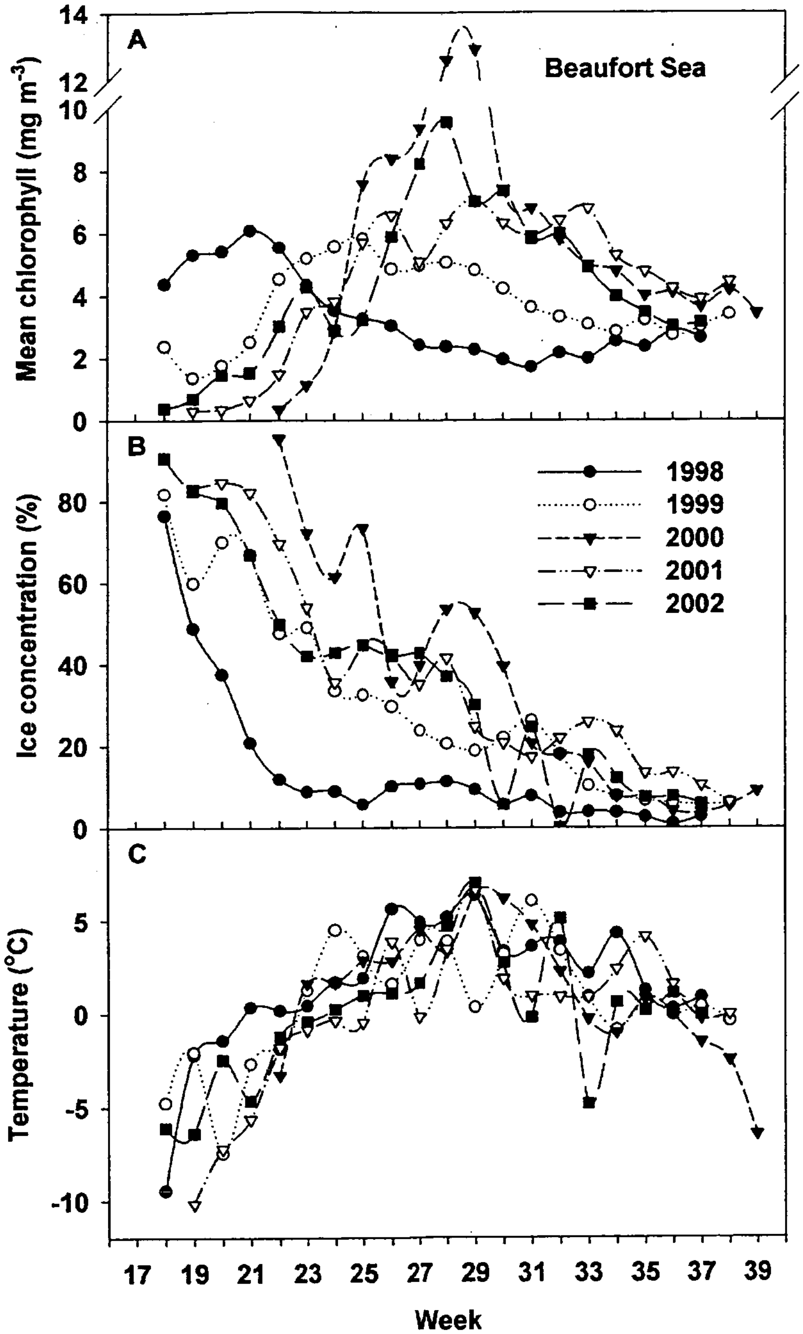
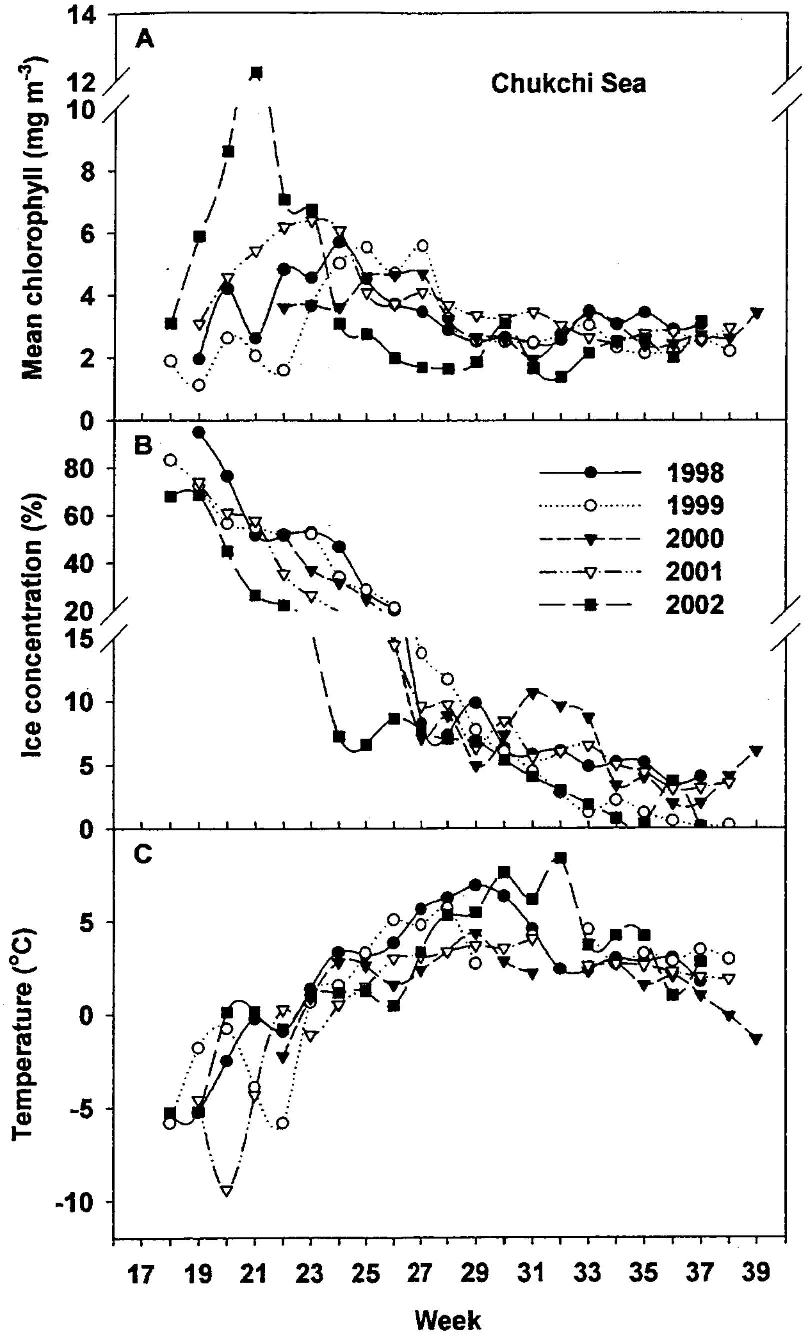
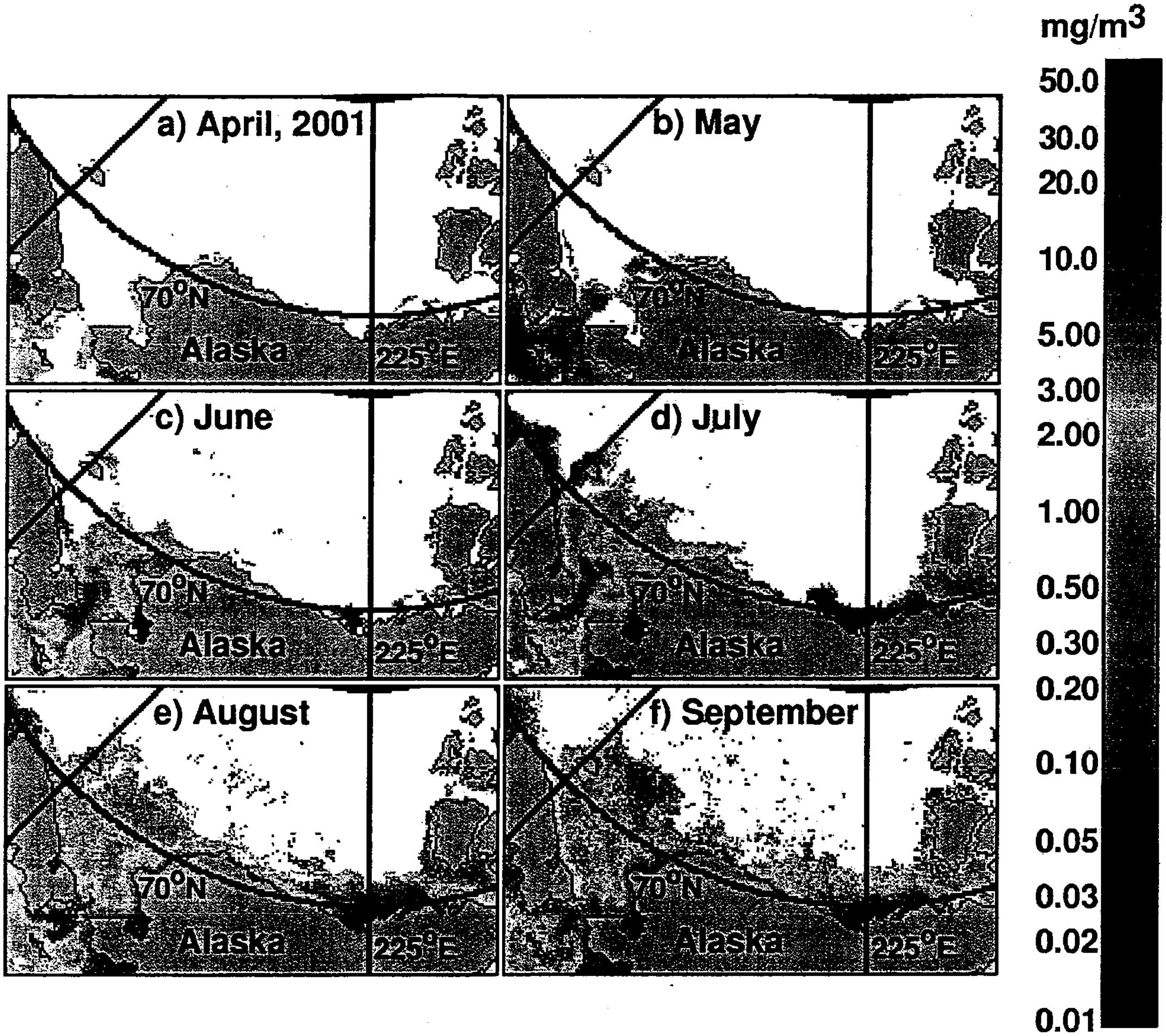

A
Beaufort Sea
Mean chlorophyll (mg m-3)
B
1998
1999
2000
2001
2002
Ice concentration (%)
C
Temperature (°C)
Week

Fig.5



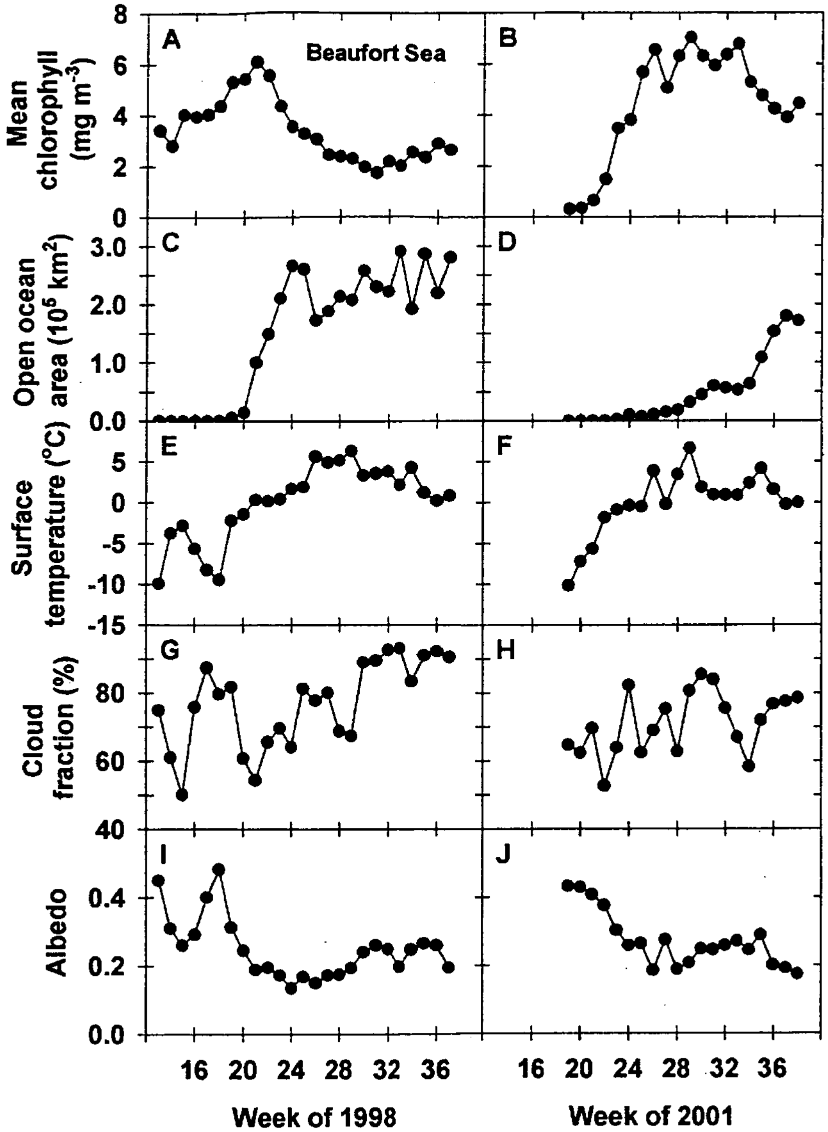
A
Chukchi Sea
Mean chlorophyll (mg m-3)
B
Ice concentration (%)
1998
1999
2000
2001
2002
C
Temperature (°C)
Week

Fig. 6



a) April, 2001
b) May
c) June
d) July
e) August
f) September
70°N
Alaska
225°E
mg/m3
50.0
30.0
20.0
10.0
5.00
3.00
2.00
1.00
0.50
0.30
0.20
0.10
0.05
0.03
0.02
0.01

Fig. 7



Beaufort Sea
A
B
C
D
E
F
G
H
I
J
Mean chlorophyll (mg m-3)
Open ocean area (10^5 km^2)
Surface temperature (°C)
Cloud fraction (%)
Albedo
Week of 1998
Week of 2001

Fig. 8

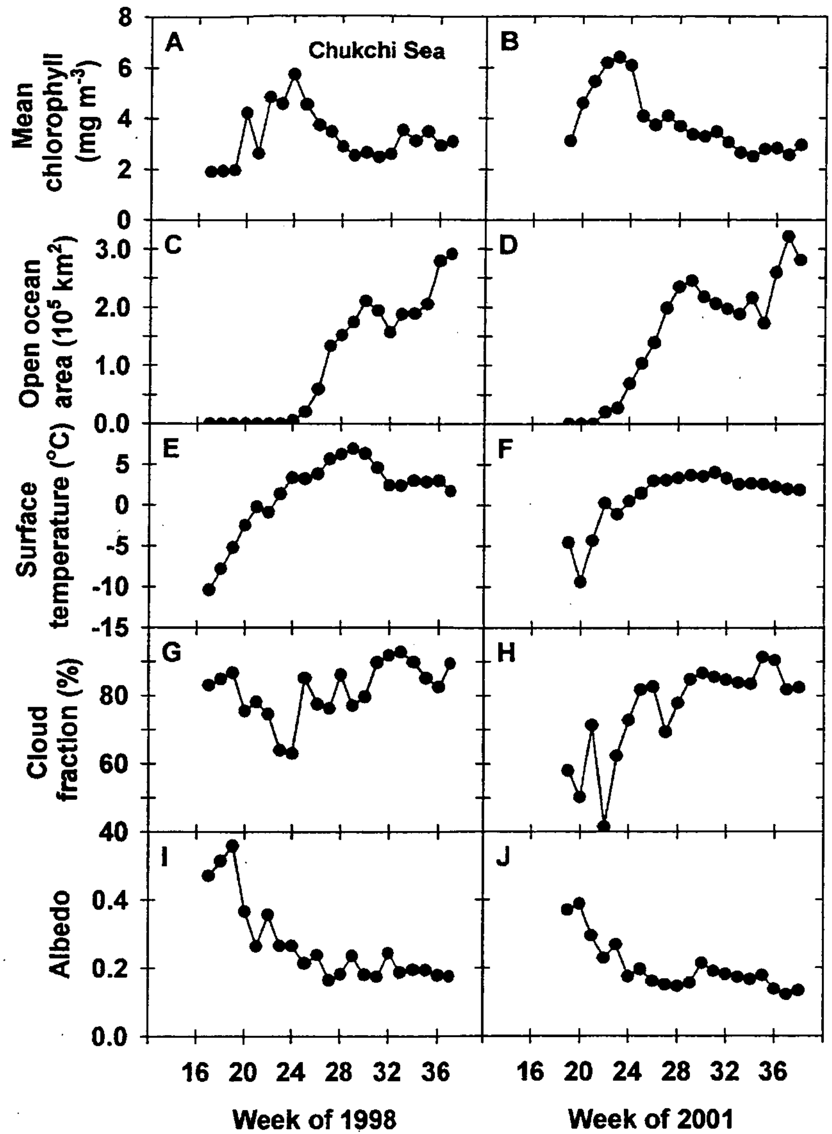

Chukchi Sea
A
B
C
D
E
F
G
H
I
J
Mean chlorophyll (mg m-3)
Open ocean area (10^5 km^2)
Surface temperature (°C)
Cloud fraction (%)
Albedo
8
6
4
2
0
3.0
2.0
1.0
0.0
5
0
-5
-10
-15
80
60
40
0.4
0.2
0.0
16 20 24 28 32 36
16 20 24 28 32 36
Week of 1998
Week of 2001

Fig. 9

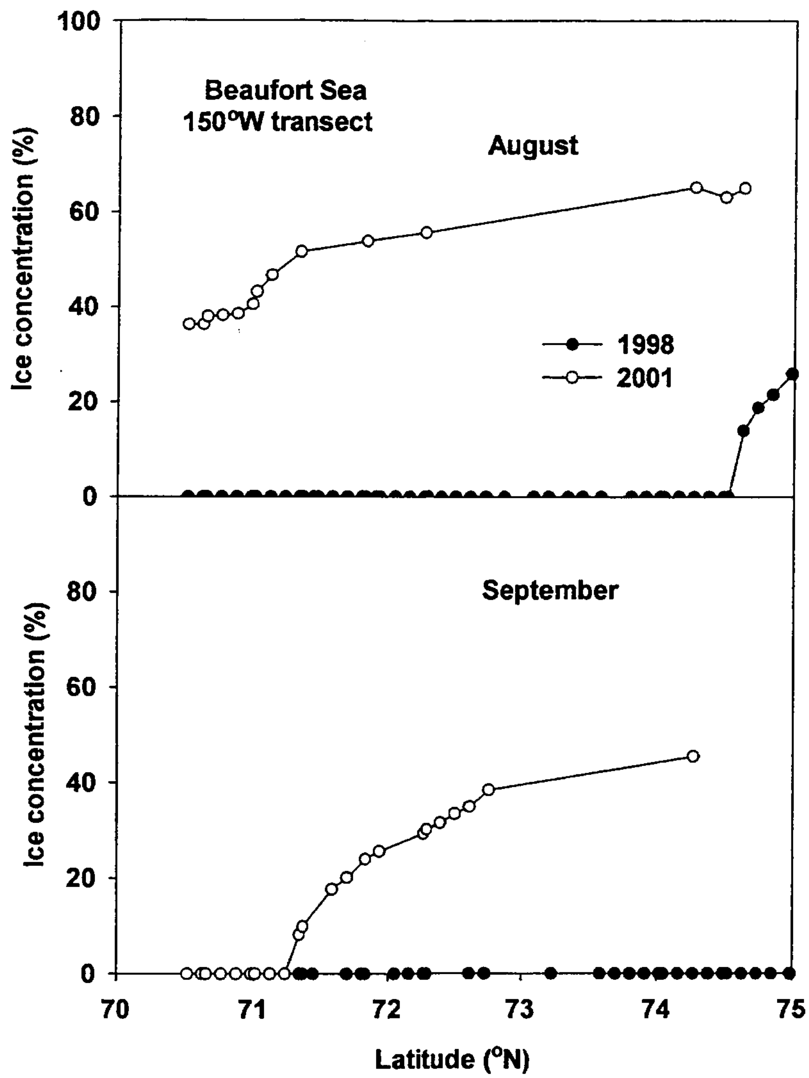

Beaufort Sea
150°W transect
August
September
1998
2001
Ice concentration (%)
Latitude (°N)
100
80
60
40
20
0
70
71
72
73
74
75

Fig. 10

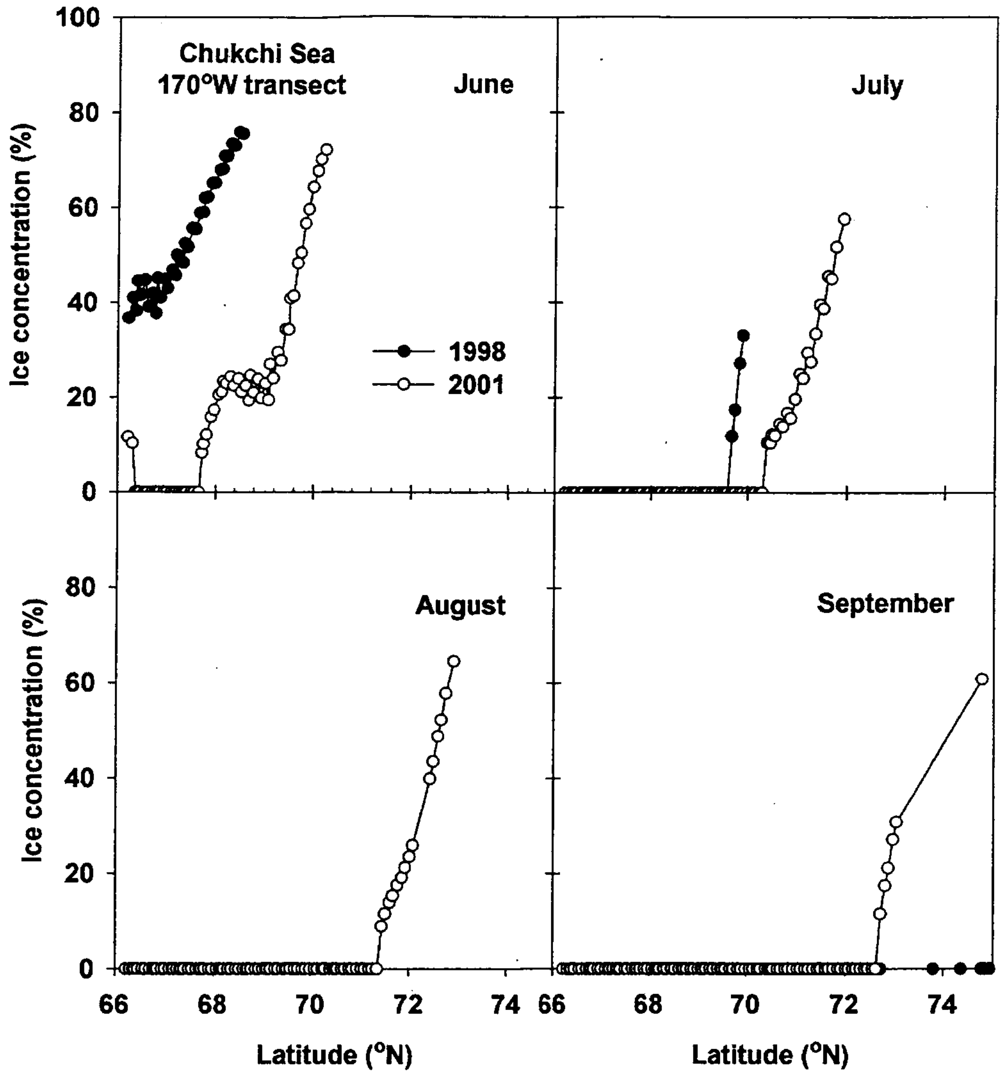

Chukchi Sea
170°W transect
June
July
August
September
1998
2001
Ice concentration (%)
Ice concentration (%)
Latitude (°N)
Latitude (°N)
100
80
60
40
20
0
66
68
70
72
74

Fig. 11